

GPS World, *Innovation* Autonomous Navigation at High Earth Orbits

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Calculating a spacecraft's precise location at high orbital altitudes—22,000 miles (35,800 km) and beyond—is an important and challenging problem. New and exciting opportunities become possible if satellites are able to autonomously determine their own orbits. First, the repetitive task of periodically collecting range measurements from terrestrial antennas to high altitude spacecraft becomes less important—this lessens competition for control facilities and saves money by reducing operational costs. Also, autonomous navigation at high orbital altitudes introduces the possibility of autonomous station keeping. For example, if a geostationary satellite begins to drift outside of its designated slot it can make orbit adjustments without requiring commands from the ground. Finally, precise onboard orbit determination opens the door to satellites flying in formation—an emerging concept for many scientific space applications.

The realization of these benefits is not a trivial task. While the navigation signals broadcast by GPS satellites are well suited for orbit and attitude determination at lower altitudes, acquiring and using these signals at geostationary (GEO) and highly elliptical orbits (HEO) is much more difficult. This situation is illustrated in Figure 1.

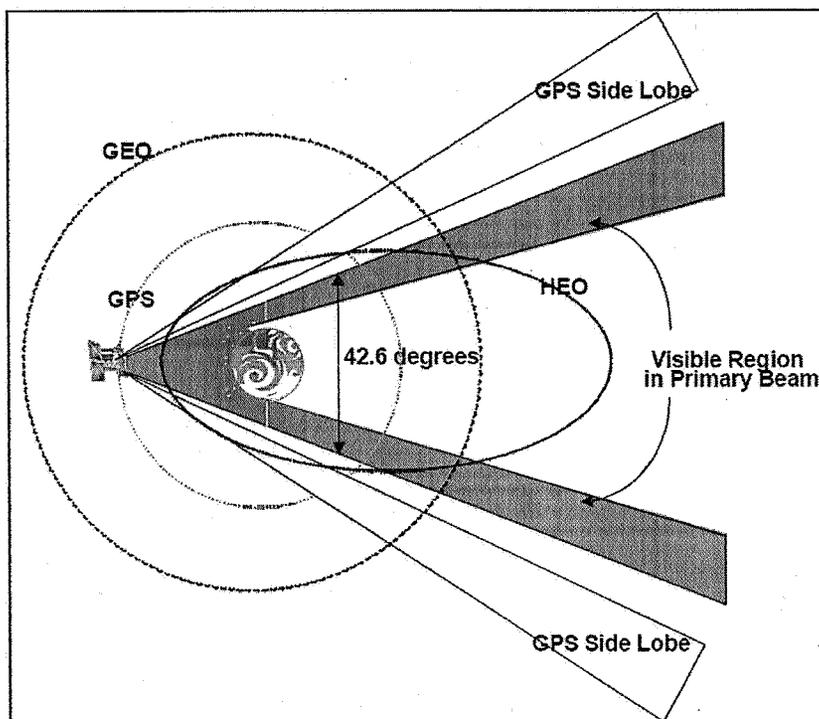


Figure 1: GPS Signal Reception at GEO and HEO Orbital Altitudes

The light blue trace describes the GPS orbit at approximately 12,550 miles (20,200 km) altitude. GPS satellites were designed to provide navigation signals to terrestrial users—consequently the antenna array points directly toward the earth. GEO and HEO orbits, however, are well above the operational GPS constellation, making signal reception at these altitudes more challenging. The nominal beamwidth of a Block II/IIA GPS satellite antenna array is approximately 42.6 degrees. At GEO and HEO altitudes, most of these primary beam transmissions are blocked by the Earth, leaving only a narrow region of nominal signal visibility near opposing limbs of the earth. This region is highlighted in gray. If GPS receivers at GEO and HEO orbits were designed to use these higher power signals only, precise orbit determination would not be practical. Fortunately, the GPS satellite antenna array also produces side lobe signals at much lower power levels. NASA has designed and tested the Navigator, a new GPS receiver that can acquire and track these weaker signals, thereby dramatically increasing the signal visibility at these altitudes.

While using much weaker signals is a fundamental requirement for a high orbital altitude GPS receiver, it is certainly not the only challenge. There are other unique characteristics of this application that must also be considered. For example, Position Dilution of Precision (PDOP) figures are much higher at GEO and HEO altitudes because visible GPS satellites are concentrated in a much smaller area with respect to the spacecraft antenna. These poor PDOP values contribute considerable error to the point solutions calculated by the spacecraft GPS receiver.

Finally, spacecraft GPS receivers must be designed to withstand a variety of extreme environmental conditions. Variations in acceleration between launch and booster separation are extreme. Temperature gradients in the space environment are also severe. Furthermore, radiation effects are a major concern—spacecraft-borne GPS receivers must be designed with radiation-hardened electronics to guard against this phenomenon, otherwise they simply will not work. Perhaps most importantly, there are no opportunities to repair or modify any space-borne GPS receiver after it has been launched. Great care must be taken to ensure all performance characteristics have been analyzed prior to liftoff.

Motivation

As mentioned earlier, for a GPS receiver to autonomously navigate at altitudes above the GPS constellation, its acquisition algorithm must be sensitive enough to pick up signals far below that of the standard space receiver. This concept is illustrated in Figure 2. The colored traces represent individual GPS satellite signals. The topmost dotted line represents the typical threshold of traditional receivers. It is evident that such a receiver would only be able to track a couple of the strong, main lobe, signals at any given time, and would have outages that can span several hours. The lower dashed line represents the design sensitivity of the Navigator receiver. The 10 dB reduction allows the Navigator to acquire and track the much weaker side lobe signals. These side lobes augment the main lobes when available, and almost completely eliminate any GPS signal

outages. This improved sensitivity is made possible by the specialized acquisition engine built into the Navigator's hardware.

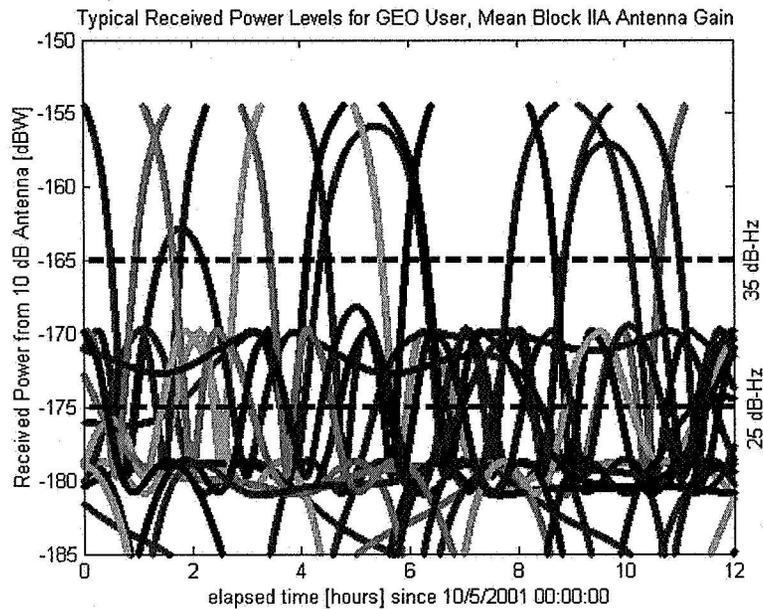


Figure 2: Simulated Received Power at GEO

Acquisition Engine

Signal acquisition is the first, and possibly most difficult, step in the GPS signal processing procedure. The acquisition task requires a search across a three-dimensional parameter space that spans the unknown time delay, Doppler shift, and the GPS satellite number. In space applications, this search space can be extremely large, unless knowledge of the receiver's position, velocity, current time, and the location of the desired GPS satellite are available beforehand. The standard approach to this problem is to partition the unknown Doppler-delay space into a sufficiently fine grid and perform a brute force search over all possible grid points. Traditional receivers use a handful of tracking correlators to serially perform this search. Without sufficient a priori information, this process can take 10-20 minutes in a Low Earth Orbit (LEO), or even terrestrial applications, and much longer in high altitude space applications.

Acquisition speed is relevant to the weak signal GPS problem, because acquiring weak signals requires the processing of long data records. As it turns out, using serial search methods (without prior knowledge) for weak signal acquisition results in prohibitively long acquisition times.

Many newer receivers have added specialized fast-acquisition capability. Some employ a large array of parallel correlators, while other use (32-128 point) Fast Fourier

Transform (FFT) methods to efficiently resolve the frequency dimension. These methods can significantly reduce the acquisition time. Another use of the FFT in GPS acquisition can be seen in FFT-correlator based block processing methods, which offer dramatically increased acquisition performance by searching the entire time-delay dimension at once. These methods are popular in software receivers, but due to their complexity, are not generally used in hardware receivers.

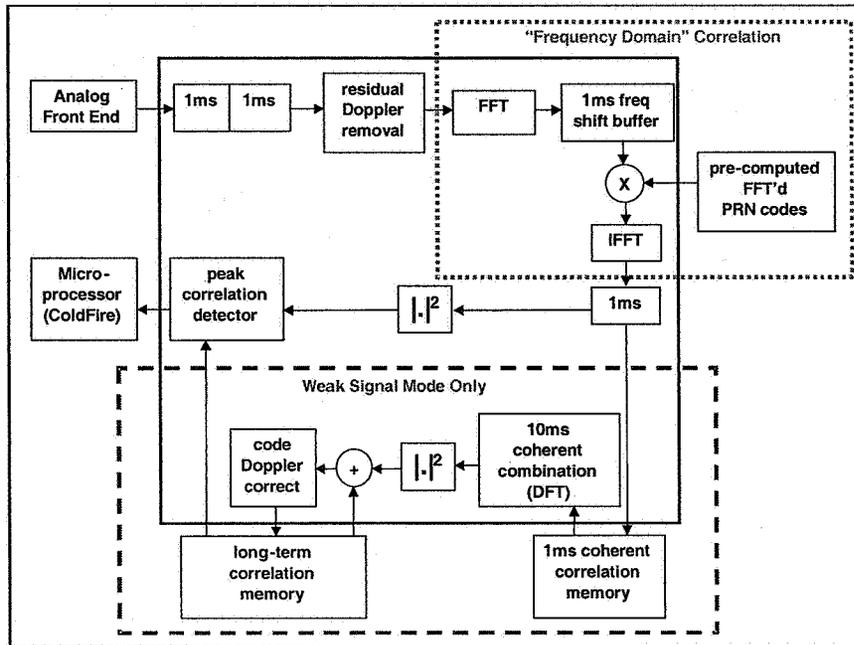


Figure 3: Navigator Signal Acquisition Engine

Navigator utilizes a highly specialized hardware acquisition engine that is designed around an FFT correlator. This engine can be thought of as more than 300,000 correlators working in parallel to search the entire delay-Doppler space for any given satellite. The module operates in two distinct modes: Strong Signal Mode and Weak Signal Mode. Strong Signal Mode processes a 1ms data record and can acquire all signals above -160 dBW in just a few seconds. Weak Signal Mode has the ability to process arbitrarily long data records to acquire signals down to and below -175 dBW. At this level, 0.3 seconds of data are sufficient to reliably acquire a signal.

Additionally, because the strong, main-lobe, signals do not require the same sensitivity as the side-lobe signals, the Navigator can vary the length of the data records, thus adjusting its sensitivity on the fly. Using essentially standard Phase Lock Loop/Delay Lock Loop (PLL/DLL) tracking methods, Navigator is able to track signals down to approximately -175 dBW. When this tracking loop is combined with the acquisition engine, the result is the desired 10dB sensitivity improvement over traditional receivers. The Navigator's acquisition engine is depicted in Figure 3.

Powered by this design, the Navigator is able to rapidly acquire all of the GPS satellites in view, even with no prior information. In a LEO, Navigator typically acquires all in-view satellites within one second, and has a position solution as soon as it has

finished decoding the ephemeris from the incoming signal. In a GEO orbit, acquisition time is still typically under a minute.

Navigator Hardware

Outside of this unique acquisition module, Navigator employs the traditional receiver architecture consisting of a bank of hardware tracking correlators attached to an embedded microprocessor. Navigator's GPS signal processing hardware, including both the tracking correlators and the acquisition module, is implemented in radiation-hardened field programmable gate arrays (FPGAs). The use of FPGAs, rather than an application specific integrated circuit (ASIC), allows for rapid customization for the unique requirements of upcoming missions. For example, when the L2 Civil signal is implemented in the Navigator, it will only require a FPGA code change, not a board redesign.

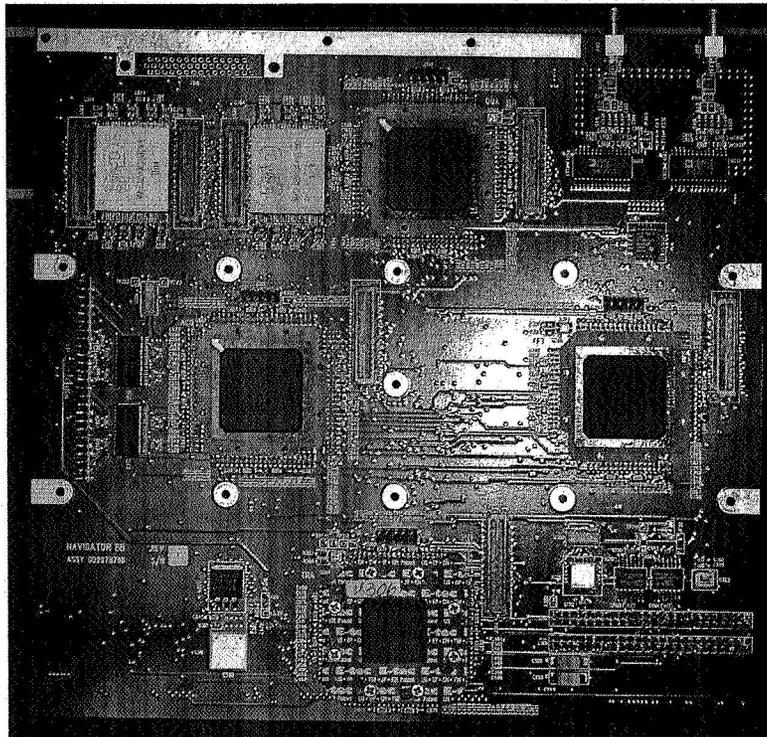


Figure 4: Navigator Breadboard

Figure 4 shows the current Navigator breadboard, lacking only the CPU card. The flight version employs a single card design and, as of the writing of this article, is in the board layout phase. Flight-ready cards will be delivered in October of 2006.

Integrated Navigation Filter

Even with its acquisition engine and increased sensitivity, the Navigator is not always able to track the four satellites required for a point solution in GEO. This limitation is especially apparent at GEO altitudes and above. To overcome this circumstance, the GPS Enhanced Onboard Navigation System (GEONS) has been integrated into the receiver software. GEONS is a powerful extended Kalman filter with a small package size, and is ideal for flight software integration. This filter utilizes its internal orbital dynamics model in conjunction with the incoming measurements to generate a smooth solution, even if there are fewer than 4 GPS satellites in view.

The GEONS filter combines its high-fidelity orbital dynamics model with the incoming measurements in order to produce a smoother solution than the standard GPS point solution. Additionally, GEONS is able to generate state estimates with any number of visible, and can even propagate through GPS coverage outages with minimal loss of solution accuracy.

Hardware Test Setup

An external, high fidelity orbit propagator was used to generate a two-day GEO trajectory, which was used as input for the Spirent STR4760 GPS simulator. This equipment, shown in Figure 5, combines the receiver's true state with its current knowledge of the simulated GPS constellation to generate the appropriate radio frequency (RF) signals as they would appear to the receiver's antenna. Since there is no physical antenna, the Spirent SimGEN® software package provides the capability to model one in software.

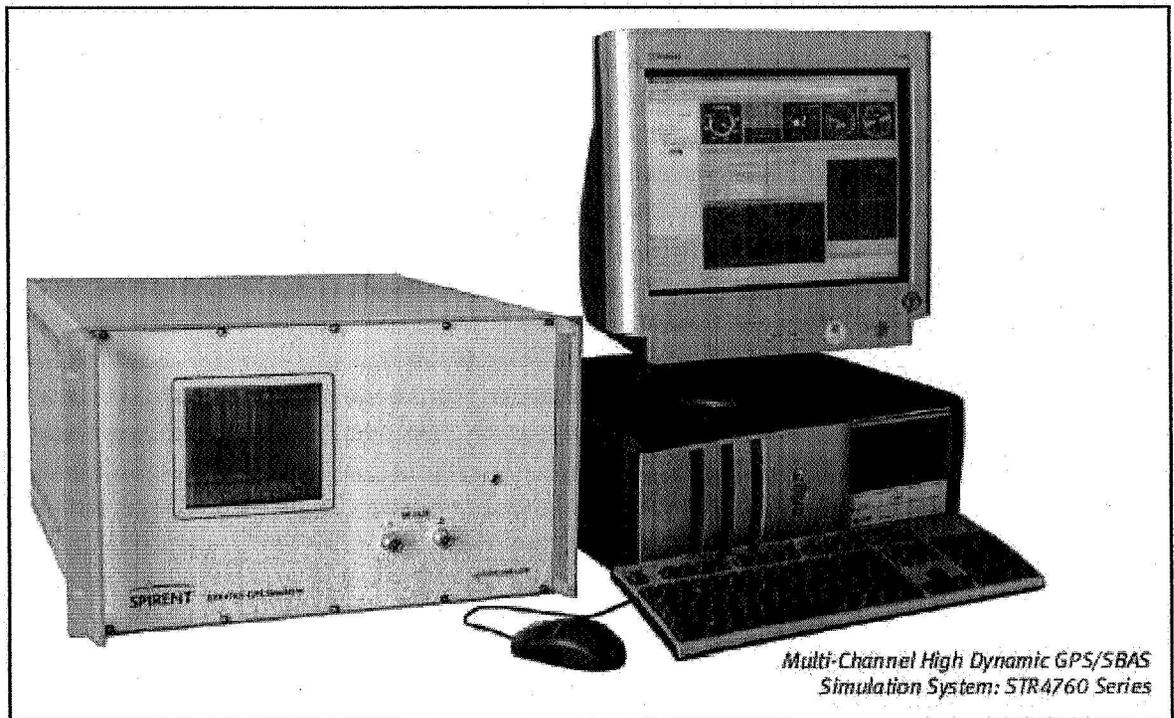


Figure 5 Spirent STR4760 GPS Constellation Simulator

The Navigator receiver begins from a cold start, with no a-priori knowledge of its position, the position of the GPS satellites, or the current time. Despite this lack of information, the Navigator typically acquires its first satellites within a minute, and often has its first position solution within a few minutes, depending on the number of GPS satellites in view. Once a position solution has been generated, the receiver initializes the GEONS navigation filter and provides it with measurements on a regular, user-defined basis. The Navigator point solution is output when available through a high speed data acquisition card, and the GEONS state estimates, covariance, and measurement residuals are exported through a serial connection for use in data analysis and post-processing.

The GPS simulator was configured to model the receiving antenna as a hemispherical antenna with a 135-degree field-of-view and 4 dB of received gain. This antenna would not be optimal for the GEO case. Assuming a nadir pointing antenna, all GPS signals are received within about an 80 deg, two-sided elevation angle. Furthermore no signals arrive from between 0 and 23 deg elevation because the earth obstructs this range. An optimal GEO antenna (possibly an array) would push all of the gain into the feasible elevations for signal reception, which would greatly improve signal visibility for Navigator (a traditional receiver would still not see the side-lobes however). Nonetheless, the following results provide an important baseline and demonstrate that a high-gain antenna, which would increase size and cost of the receiver, may not be necessary with

Navigator. The GPS satellite transmitter gain patterns were set to model the Block II/IIA L1 reference gain pattern.

Simulation Results

In order to validate the receiver designs, several tests were run using the configuration described above. The following section describes the results from a subset of these tests.

Number of tracked satellites

The top plot of Figure 6 illustrates the total number of satellites tracked by the Navigator receiver during a two day run with the hemispherical antenna. On average, Navigator tracked between 3 and 4 satellites over the simulation. The middle pane depicts the number of weak signals that were tracked, and the bottom panel shows how many satellites a typical space receiver would pick up. It is evident that the Navigator can track 2-3 times as many satellites at GEO as a typical receiver, and that most of these signals are weak.

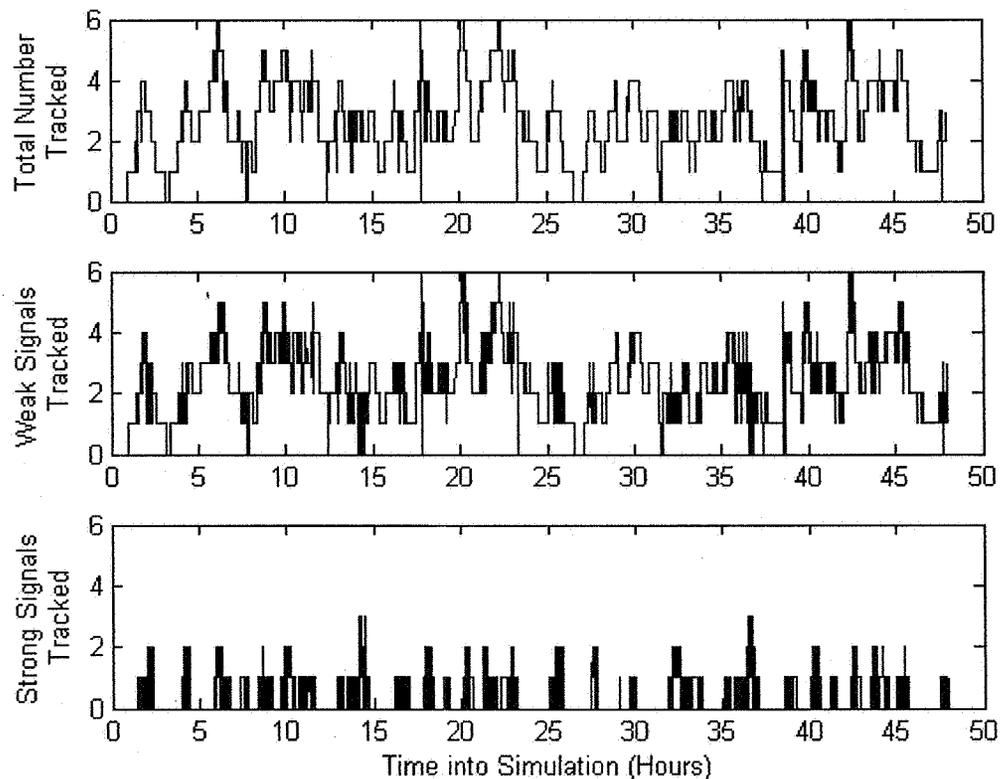


Figure 6: Number of Satellites Tracked

Acquisition Thresholds

The received power of the signals tracked with the hemispherical antenna is plotted in the top half of Figure 7. The lowest power level recorded was approximately -178dBW, 3 dBW below the design goal. (note the difference in scale from Figure 1, which assumed an additional 6dB of antenna gain) The bottom half of Figure 7 shows a histogram of the tracked signals. It is clear to see that most of the signals tracked by the Navigator had received power levels around -175 dBW, 10dBW weaker than a traditional receiver's acquisition threshold.

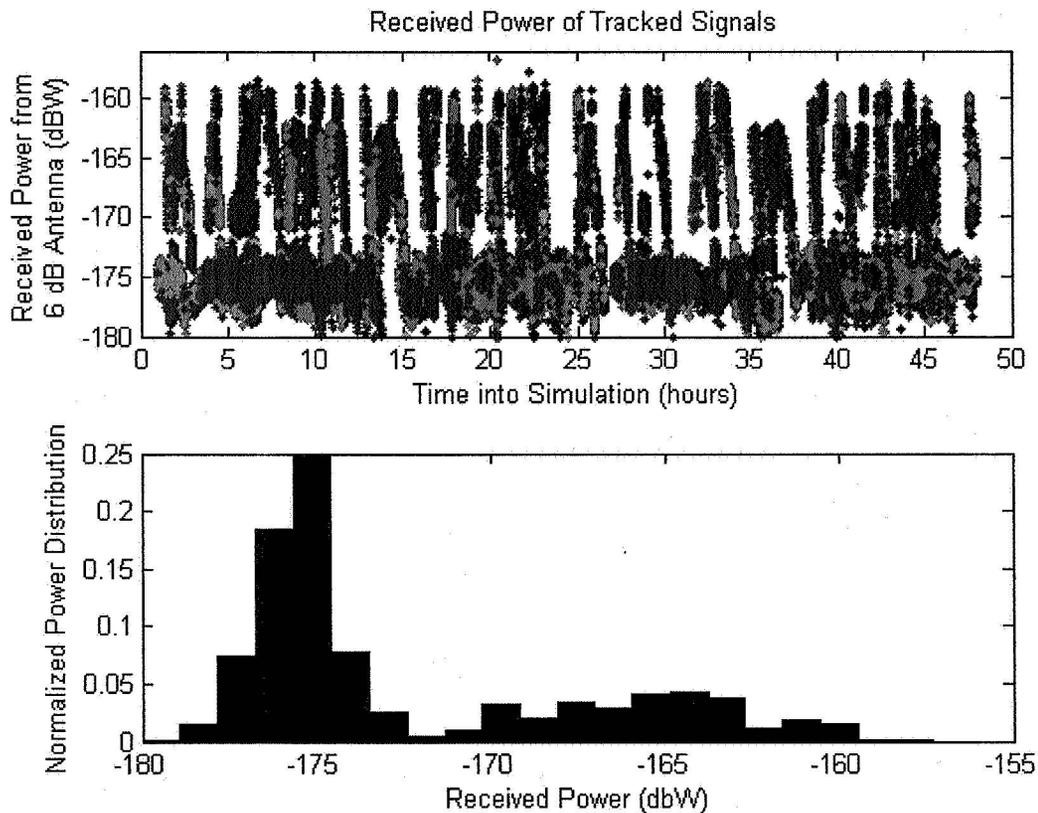


Figure 7 Signal Tracking Data

Navigation Filter Performance

In order to validate the integration of the GEONS software, its estimated states were compared to the true states over the two-day period. These results are plotted in Figure 8. For this simulation, it was assumed that the GPS satellite clock and ephemeris errors could be corrected by applying NASA's Global Differential GPS Corrections, and the errors caused by the ionosphere could be removed by masking those signals that passed close to the limb of the Earth. The truth environment consisted of a 70x70 gravity model, sun and moon gravitational effects, as well as drag and solar radiation pressure forces. GEONS internally modeled a 10x10 gravity field, solar and lunar gravitational forces, and estimated corrections to drag and solar radiation pressure parameters. Though

the receiver produces pseudorange, carrier-phase, and Doppler measurements, only the pseudorange measurement is currently being processed in GEONS.

The results, compiled into Table 1 show that the 3-D root mean square of the position error was less than 10 meters after the filter converges. The velocity estimation agreed very well with the truth, exhibiting less than 1 mm/s of three dimensional error.

Navigator can provide excellent GPS navigation data at LEO as well with the added benefit of near instantaneous cold-start signal acquisition. For completeness, the results for a low Earth orbit (LEO) are included as well.

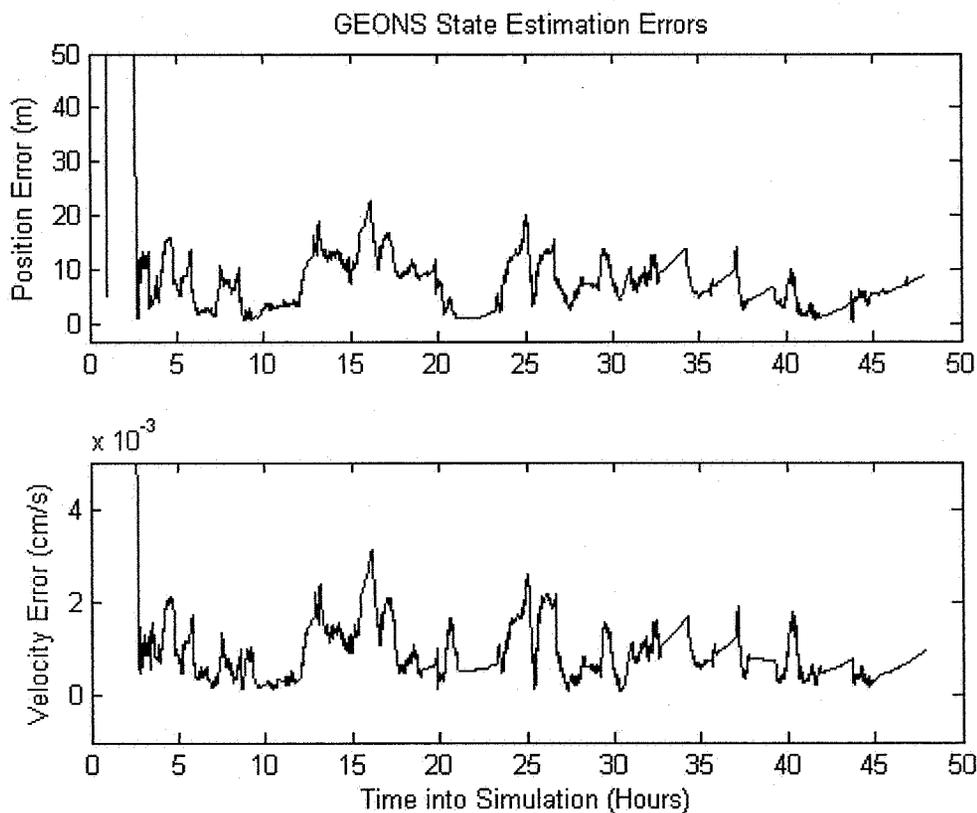


Figure 8 GEONS State Estimation errors

Table 1: GEONS Estimation Error Statistics

	Radial	Intrack	Crosstrack	3D-RMS
GEO ORBIT				
Position (m)	-4.424 ± 5.640	-0.546 ± 2.265	0.675 ± 2.462	7.9591
Velocity (cm/s)	-0.038 ± 0.076	-0.133 ± 0.051	-0.001 ± 0.025	0.09634
LEO ORBIT				
Position (m)	0.036 ± 0.747	0.215 ± 0.995	0.103 ± 0.860	1.5320
Velocity (cm/s)	-0.022 ± 1.613	0.002 ± 0.079	0.0243 ± 0.1071	0.21044

Navigator's Future

Navigator's unique features have attracted the attention of several different NASA projects. In 2007, the Navigator is scheduled to launch onboard the Shuttle as part of the Hubble Space Telescope Servicing Mission 4: Relative Navigation Sensor (RNS) experiment. Additionally, the Navigator/GEONS technology is currently being considered as a critical navigational instrument on the new Geostationary Operational Environmental Satellites (GOES-R). In another project, the Navigator receiver is being mated with the Intersatellite Ranging and Alarm System (IRAS) as a candidate absolute/relative state sensor for the Magnetospheric Multi-Scale Mission (MMS). This mission will transition between several high-altitude highly-elliptical orbits that stretch well beyond GEO. Initial investigations and simulations using the Spirent simulator have shown that Navigator/GEONS can easily meet the mission's positioning requirements where other receivers would certainly fail.

Conclusion

NASA's Goddard Space Flight Center has conducted extensive test and evaluation of the Navigator GPS receiver and GEONS orbit determination filter. Test results, including data from RF signal simulation, indicate the receiver has been designed properly to autonomously calculate precise orbital information at altitudes of GEO and beyond. This is a remarkable accomplishment given the weak GPS satellite signals observed at these altitudes. The GEONS filter is able to utilize the measurements provided by the Navigator receiver to calculate precise orbits to within 10 meters 3D RMS (typical). Actual flight test data from future missions including the Space Shuttle RNS experiment will provide further performance characteristics of this equipment, from which its suitability for higher orbit missions such as GOES-R and MMS can be confirmed.

Manufacturers

The Navigator receiver was designed by the NASA Goddard Space Flight Center Components and Hardware Systems Branch (Code 596) with support from various contractors. The 12-channel RF GPS signal simulator was manufactured by Spirent Communications.

For Further Reading

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